

This is the peer reviewed version of the paper:

Stratimirović, Đorđe, Batas-Bjelić, Ilija, Đurđević, Vladimir, Blešić, Suzana, "Changes in long-term properties and natural cycles of the Danube river level and flow induced by damming" *Physica A: Statistical Mechanics and its Applications*, 566 (2021):125607, <https://doi.org/10.1016/j.physa.2020.125607>.



This work is licensed under a [Creative Commons Attribution Non Commercial No Derivatives 4.0](https://creativecommons.org/licenses/by-nc-nd/4.0/) license

Changes in long-term properties and natural cycles of the Danube river level and flow induced by damming

Djordje Stratimirovic^{a,1}, Ilija Batas-Bjelic^b, Vladimir Djurdjevic^c, Suzana Blesic^{d,*}

^a*Faculty of Dental Medicine, University of Belgrade, Dr Subotica 8, Belgrade, 11000, Serbia*

^b*Institute of Technical Sciences, Serbian Academy of Sciences and Arts, Knez Mihajlova 35, Belgrade, 11000, Serbia*

^c*Faculty of Physics, Institute for Meteorology, University of Belgrade, Studentski trg 16, Belgrade, 11000, Serbia*

^d*Department of Environmental Sciences, Informatics and Statistics, Ca'Foscari University of Venice, Via Torino 155, Venezia, 30170, Veneto, Italy*

Abstract

In this paper we assessed changes in scaling properties of the river Danube level and flow data, associated with building of Djerdap/Iron Gates hydrological power plants positioned on the border of Romania and Serbia. We used detrended fluctuation analysis (DFA), wavelet transform spectral analysis (WTS) and wavelet modulus maxima method (WTMM) to investigate time series of measurements from hydrological stations in the vicinity of dams and in the area of up to 480 km upstream from dams, and time series of simulated NOAA-CIRES 20th Century Global Reanalysis precipitation data for the Djerdap/Iron Gates region. By comparing river dynamics during the periods before and after construction of dams, we were able to register changes in scaling that are different for recordings from upstream and from downstream (from dams) areas. We found that damming caused appearance of human-made or enhancement of natural cycles in the small time scales region, which largely influenced the change in temporal scaling in downstream recording stations. We additionally found disappearance or decline in the amplitude of large-time-scale cycles as a result of damming, which changed the dynamics of upstream data. The most prominent finding of our paper is a demonstration of a complete or partial loss of annual cycles in the upstream stations' data that stems from the operation of the artificial water reservoir and extends as far as 220 km from dams. We discussed probable sources of such found changes in scaling, aiming to provide explanations that could be of use in future environmental assessments.

Keywords: river level and flow, hydro-power plants, scaling analysis, natural cycles

1. Introduction

Since the initiation of present-day scaling techniques in statistical hydrology [1], the role of stochasticity in river flow dynamics has been extensively studied. The original work of Hurst [1, 2] demonstrated the existence of a power-law-type time dependence of statistical functions describing river discharges that seemed to be widespread in the dataset of world rivers available at the time. This was an empirical proof that "the natural phenomena [so far considered] have a similarity amongst themselves but differ from purely chance phenomena" [2]. Statistics and dynamics of river discharges have been since analysed in a number of studies that used both traditional statistical methods, and methods inspired by the analyses of Hurst. A plethora of thus produced further empirical results confirmed the original findings of the existence of scaling in time series of river levels and flows, informing on the ubiquity of memory in river flow dynamics (see, e.g., [3] and [4] and references therein, [5] and studies of scaling in river flows mentioned therein, or [6–10]), and extending them to the research into details of the complexity of this dynamics, including comprehensive examination of nature and sources of non-stationarity in river hydrological records [11–15], or multifractality of its behavior [3]. We offer the addition to this body of knowledge that examines human-induced alterations in long-range order of river flows caused by damming, aiming to provide research for future interdisciplinary programs linking hydrology and hydro power with climate and environment [16].

As an important technical innovation of humankind, dams are supporting our living by regulating river flows for flood control, irrigation support and electricity production, and hold at least a part of a central stage in recent increasing desire for non-fossil fuel-based energy [16–19]. At the same time, however, researchers in ecohydrology, closely following these developments, provide evidence about ecological consequences of hydro power river

*Corresponding author.

Email addresses: `dj.stratimirovic@gmail.com` (Djordje Stratimirovic), `ilija.batas@gmail.com` (Ilija Batas-Bjelic), `vdj@ff.bg.ac.rs` (Vladimir Djurdjevic), `blesic.suzana@gmail.com` (Suzana Blesic)

flow management and regulation, such as the decrease in water quality and impact on the exchange of sediments, nutrients, and organisms between and among aquatic and terrestrial regions [20–22], or central role in species shifts and increased mortality rates of aquatic species migrating downstream [23–25]. They additionally report damming to induce changes in biogeochemical river cycles [26], resulting, among other, in methane emissions contributing to global climate change [16, 17]. With this in mind, in this study we specifically investigate how damming affects scaling dynamics and cyclical consistency, in the case study of the Danube river flow, aiming to provide characterization of physical changes of river dynamics for potential environmental concerns and/or restrictions to future optimization, planning and design of dams.

Danube is the second largest river in Europe. Its importance spans a vast variety of research interests, from studies of the water balance along the river [27–29], to researches of the anthropogenic pressure that over 165 million persons that it connects exert on its dynamics and surroundings [25, 30, 31]. Modern hydraulic interventions in the Danube river basin resulted in the construction of eight dams in the period 1956-1985; of those the most ambitious waterworks, the hydro power and navigation systems of Djerdap (or Iron Gates) I and II, were constructed over the period 1964-1985 by the joint efforts of Romania and former Yugoslavia (SFRY). The dam for the hydro power plant Djerdap (or Iron Gate) I was constructed in 1972, positioned at 943 km from the Black Sea, producing a formation of the reservoir of 3500 million m³ in volume under average hydrological conditions [32], an increase of about 2100 million m³ compared to the previous (natural) channel. By 1984, the second dam, Djerdap (or Iron Gate) II was constructed and operational, 80 km downstream from the first dam, built basically to compensate the regulation of water level in the lower pool of the first dam [29]. Construction of these dams was thus a big enough endeavour to substantially change the morphology of the river and disturb its natural equilibrium, both upstream and downstream. Having in mind that the two dams were constructed in the relative vicinity to each other, and that the whole intervention resides inside of a canyon that river Danube forms in this region, we hypothesized that this would present with a conveniently confined natural system that will allow to study the influence of damming

December 28, 2020

on the river flow dynamics. It was our presumption that, provided that reasonably long historical records are available, and in the absence of significant effects of any other major local hydroclimatic mechanism [33], any change in the river dynamics that we find when comparing records in the periods before and after constructions of dams can be attributed to the change in physical conditions at the location of individual hydrological measuring stations that is induced by damming.

We present a map of a geographic area surrounding the dams in Figure 1. Throughout this area the precipitation, a major component of the hydrological cycle that determines river levels and river flows, is present during the entire year. Generally, in the colder part of the year, precipitation is dominantly linked to extratropical cyclones, and in the warmer part of the year precipitation is linked with convective thunderstorm systems. During the winter snow substantially contributes to precipitation totals. Monthly precipitation maximum is observed for the months at the beginning of summer, but also secondary maximum can present in the beginning of winter, with often substantial contribution of snow.

According to the SFRY energy planning sources [34], the energy planning for dams is performed using the level at river Nera confluence as referent for all arbitrages. The levels of weekly storage of dams were optimally designed a year in advance at first, with the previous 50 years of daily measurements as referent value. Later, fine-tuning of planning was done on a weekly scale, while today, for Djerdap/Iron Gate I (DAM1), which operates as a storage dam (production of electricity may be postponed for around a day), hourly operations are defined one day in advance. Typically, this daily chronological production diagram compromises two peaks, daily peak at noon and evening peak at 19.30. The operation of Djerdap/Iron Gate II (DAM2) is similar, but it operates as a run-of-river dam, without a water storage. Finally, half of the dams operational system is regulated separately by Romanian planners, with real time monitoring and yearly arbitrage according to the common dispatching protocol [34].

We approach our research hypothesis by using the 2nd order detrended fluctuation analysis (DFA2) to characterize river dynamics in terms of behaviour and changes in long-range autocorrelations of the Danube river flow, by determining the DFA2 exponent α . We use DFA2 in combination with the wavelet transform power spectral analysis (WTS), to con-



Figure 1: Hydrological stations, used in this study, and dam positions. Presented region position in wider geographical area is given as a red rectangle, in the upper right box.

firm DFA2 results by determining the WTS exponent β , and to additionally examine cycles and cyclical consistency of our records. Previous studies of the long-range dependence, or long-term persistence (LTP) of the Danube river flow report on the existence of LTP in the Danube flow records, with values of α in the range from $\alpha = 0.67$ to $\alpha = 0.85$ for measuring stations in Germany, Austria, Slovakia, Hungary, and Romania, and a crossover in scaling behaviour at time scales $n_c \approx 2 - 30$ days (or, alternatively, at $20 - 100$ days) [3, 4, 35–39]. Furthermore, some of these researches inform on distinct non-linear long-range character of

the Danube river flow, manifested in strong multifractality of its records [3, 4, 37, 38]. In this, dynamical sense, Danube is not very dissimilar from other world rivers; based on these and similar findings, a general assumption was made that Danube river fluctuations most probably come about as results of combined influences of storage effects, highly intermittent spatial behaviour of rainfall, and non-linear interaction between rainfall and the river flow [3, 4, 40]. In this paper we want to assess which of the linear or non-linear features of Danube river dynamics change and which, if any, remain invariant under a particular (dam construction) anthropogenic influence.

The paper is organized as follows: Section 2 presents with a brief overview of sources of our data, and of the general methodological framework of DFA, WTS, WTMM and 20GCR (re)analyses. In sub-sections 3.1 and 3.2 we present results of our usage of DFA2 and WTS to study changes in scaling of the Danube and Danube tributaries level and flow datasets that are induced by damming. In sub-section 3.3 we present results of the DFA2-WTS analysis of the 20GCR reanalysis precipitation series for the dams area, and overview possible links of natural climate cycles to the enhancement or introduction of cycles that we observed in sub-sections 3.1 and 3.2. We end our paper with a list of conclusions and suggestions for future research in Section 4.

2. Data and Methods

2.1. Data

Records of daily Danube and Danube tributaries activity were provided by the Serbian Hydrometeorological Service (RHMZS, [41]). We were able to find hydrological stations with long enough historical records in the area of Djerdap/Iron Gates dams, out of which we selected to analyze data from hydrological stations (see Figure 1) near the town of Golubac, situated upstream from both dams (99 km upstream from DAM1, and right bellow the accumulation lake, denoted UP in the rest of the text), the town of Brza Palanka, situated in between the two dams (59 km downstream from DAM1, denoted MD from here in), and the town of Prahovo, situated downstream from both dams (2 km downstream from DAM2,

denoted DS in this paper). For these three stations only historical long records of river level were however available, thus we performed scaling analysis on the river level data that we derived from these records [35, 42]. River level and the river flow are closely dependent variables, connected by the relationship represented in a rating curve describing the cross-section of the river [43, 44]. However, this relationship is not exactly straightforward [43], and in this paper we considered these two quantities as different [45]. All the data that we used are daily records or daily averages.

We additionally analyzed records from two other hydrological stations in the Danube upstream basin, and from stations belonging to the basin of Danube tributaries Velika Morava, Sava and Tisza, with mouths in the relative upstream vicinity of the dams. Details of the stations positions and of the elements of measurements and observations for each station data used in this paper are given in Table 1.

Change in the water level is already visible from the original (hydrological stations records) time series that we obtained from RHMZS, that is, it is visible in the records of stations positioned upstream, in the relative vicinity of the dams. In Figure 2 we present such records from UP, MD, and DS stations; while the river level does not change visibly downstream from dams, it significantly changes upstream, with the building of both dams (in UP station), or after building of DAM2 (in MD). Upstream the water level increases with damming, while the fluctuations around level average (or mean) significantly decrease. This phenomenon is visible in some of the other upstream stations that we analyzed (see results below).

In scaling analysis we used deseasoned daily river level and (where available) river flow data. We eliminated strong influence of a seasonal trend in both mean and variance of records, by calculating departures $r_i = \sqrt{(R_i - \bar{R})/(\bar{R}_i^2 - \bar{R}_i^2)}$, where \bar{R}_i is the mean value for the particular date i over all years in the record [3, 46]. It is preferable whenever possible to eliminate seasonal trend against the mean value calculated over all years of the record, for in this case the annual cycle is diminished by use of the overall data statistics. We offer examples of results of the use of reference periods before and after dam construction for data deseasoning in the supplemental information to this paper. Leap days were included in our

Table 1: Recording stations positions, with the elements of measurements and observations for each station data used in this paper.

station (basin)	km from DAM1/mouth	km2 basin area	start recording year: level, flow	nota- tion
Djerdap/Iron Gates dams Danube area				
Golubac (Black Sea)	99/1042	571951	1925, –	UP
Brza Palanka (Black Sea)	-59.2/883.8	576527	1933, –	MD
Prahovo (Black Sea)	-82/861	577085	1935, –	DS
Other Danube stations				
Smederevo (Black Sea)	173.23/1116.23	525820	1921, 1946	D1
Bezdan (Black Sea)	482.59/1425.59	210250	1920, 1924	D2
Tributary Velika Morava stations (mouth approx. 170km from DAM1)				
Ćuprija (Danube)	145.41	32561	1923, 1948	VM1
Varvarin (Danube)	177.22	31548	1924, 1924	VM2
Tributary Sava stations (mouth approx. 220km from DAM1)				
Belgrade (Danube)	0.82	95719	1920, –	S1
Sremska Mitrovica (Danube)	139.24	87996	1948, 1926	S2
Tributary Tisza stations (mouth approx. 270km from DAM1)				
Titel (Danube)	8.7	157174	1930, 1965	T1

deseasoned record r_i . We performed scaling analysis on the r_i datasets and compared results for three distinct time periods: a) the time period from the beginning of recording for the particular station and the year 1969, before the construction of dams (pre-development), b) the time period from 1973 to 1983, after initiation of operations of the first dam and before construction of the second dam (post-development for DAM1), and c) the time period from 1985, after both dams were operational (post-development for DAM2).

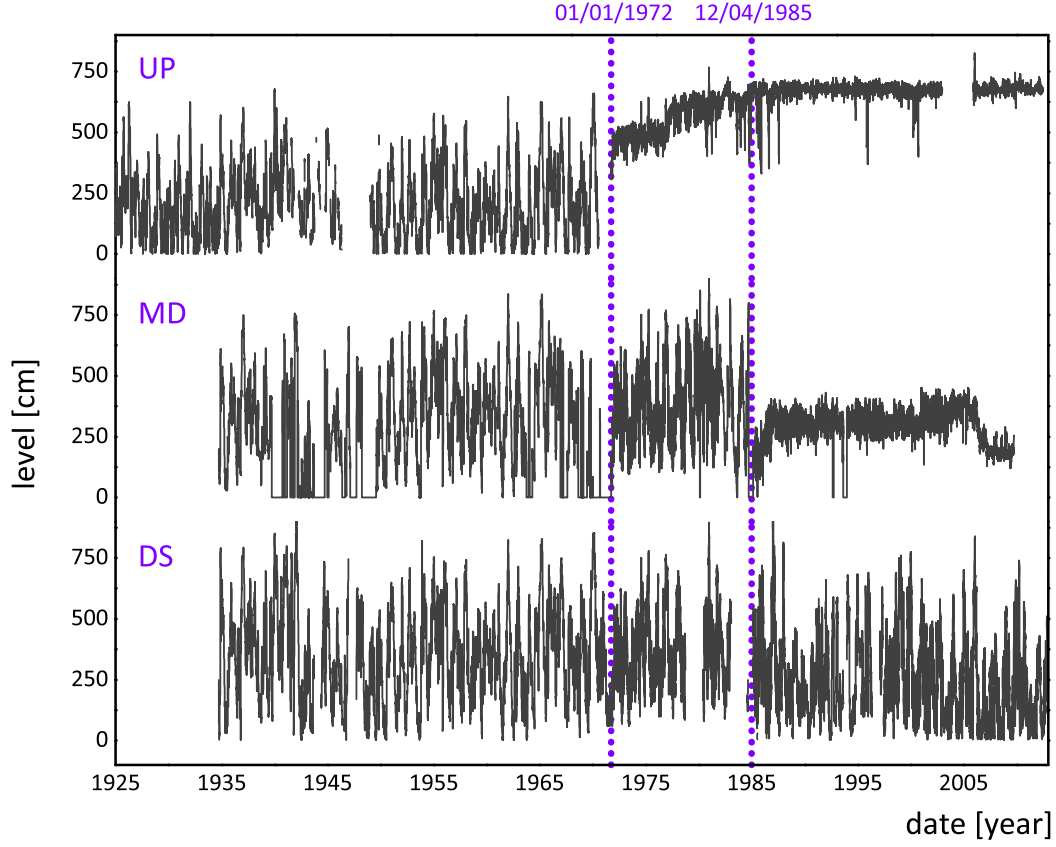


Figure 2: Danube level time series recorded at hydrological stations Golubac (UP), Brza Palanka (MD), and Prahovo (DS).

2.2. Methods

We firstly described scaling properties of river level and river flow records by calculating their scaling exponents α . To determine α , we used the 2nd order detrended fluctuation analysis (DFA2), which (among other) systematically removes linear trends in data; by method design, in DFA n trends up to order $n - 1$ are eliminated from the original record [47]. Detrended fluctuation analysis (DFA) was introduced as an appropriate scaling analysis to deal with nonstationary records that contain some trends of unknown form [48]. Recently, a new mathematical insight was provided that further explores how DFA operates on non-stationary data series with non-stationarity due to their (unknown) intrinsic dynamics [49]. We will not explain in detail the DFA2 procedure here - for theoretical and procedural

specifications we would refer to original articles that introduced DFA procedure [48], different orders of DFA (DFA_n) [47], or some of our previous utilizations of DFA and DFA2 [50, 51].

In the case of long-range autocorrelated data the DFA function $F(n)$, due to the inherent power-law data dynamics, presents as a straight line on log-log graphs of dependence of $F(n)$ of the time scale n , allowing for quantification of scaling by the corresponding power-law exponent (log-log slope) α . For data with power-law long-range autocorrelations $F(n) \sim n^\alpha$, with $\alpha \neq 0.5$; short-range autocorrelated or random data have $F(n) = n^{1/2}$ [48]. In such cases, the Fourier power spectral density decreases as a power law as well, with $E_F(\omega) \sim \omega^{-\beta}$ [52], and a power law exponent β that can be related to α through scaling relation $\alpha = (\beta + 1)/2$ [52]. This bounds α to a range $0 < \alpha < 1$ for stationary records, where $0.5 < \alpha < 1$ indicates that the record is long-term persistent. Instances when $\alpha \geq 1$, that will be of interest to the dataset used in this paper, imply the existence of intrinsic non-stationarities in autocorrelated record [49]. When this is the prevalent data dynamics, the corresponding DFA functions exhibit crossovers, while $\alpha \geq 1$ may mean that the underlying process is of a composite nature [53], or that there exists an imbalance between different noise inputs [54].

A pure long-range autocorrelated behaviour, as described above, rarely occurs in natural records; real-world data DFA2 functions, depicted on log-log graphs, are rarely ideal linear functions. Instead, they tend to contain transient crossovers in scaling that stem from occurrences of irregular phenomena of different types [55, 56], most commonly from the effects of mixtures of cyclic components that locally perturb their behaviour [7]. When effects of such irregularities are visible on DFA2 curves, but are not comparatively strong to change global behaviour of DFA2 functions, we use wavelet transform spectral analysis (WTS) to investigate them in detail. The wavelet transform (WT) method was introduced in order to circumvent the uncertainty principle problem in classical signal analysis [57] and achieve better signal localization in both time and frequency than that of the classical Fourier transform approaches [58, 59], without assuming stationarity of records. In WT, the size of an examination window is adjusted to the frequency analyzed; in this way an adequate time resolution for high frequencies and a good frequency resolution for low frequencies is

achieved in a single transform [60]. For detailed explanation of the WTS procedure used in this paper please see e.g. [58, 59, 61], or previous uses by our group in [62]. In using WTS, we standardly calculate the mean wavelet power spectra $E_W(n)$. According to the relation that connects $E_W(n)$ with its corresponding Fourier power spectrum (PwS) $E_F(\omega)$ [63], if the WTS exhibits power-law behavior, then the PwS will be of the power-law type as well, with the same power-law exponent β [62]. We standardly use Morlet wavelets of the 6th order as a wavelet basis for our analysis. Morlet wavelets provide with an optimal joint time-frequency localization [64, 65] and are particularly well adapted to estimate local regularity of functions [55]. In local power spectra Morlet wavelet is narrow in spectral (scale)-space, and broad in the time-space, which produces very well localized, relatively sharp peaks in global WT spectra, the averages of local spectra over time [65]. This allows for the reliable determination of locations and spatial distributions of both periodic or non-periodic cycles and significant singular events in non-stationary time series [55]. To assess the significance of obtained cycles - peaks in WT spectra, we utilized statistical significance testing proposed in [65], against the analyzed signal as the noise background, as explained in [57].

To study multiscaling properties of Danube data in this paper we used formalism of the wavelet transform modulus maxima (WTMM) method; for details of this procedure see, e.g., introduction in [66] and detailed description in [62]. We used WTMM to obtain distributions of the singularity spectra $D(h)$, related to the fractal dimensions of the analyzed time series [62]. For multifractal series $D(h)$ is a parabolic curve whose maximum position on the x-axis indicates the value of the (monofractal, or global) Hölder exponent H of the series, with $H = \alpha - 1$ [67]. For monofractal data $D(h)$ collapses to a single point.

Finally, in order to assess the association of changes in long-term properties of river dynamics with the local climate and climatic characteristics, we analyzed daily precipitation averaged over catchment area upstream from dams, obtained from NOAA-CIRES 20th Century Global Reanalysis Version 2 [68] and compared them with river records statistics. The 20th Century Global Reanalysis Project (20GCR) offers "an estimate of the state of the atmosphere at any particular time by forming a weighted average that combines millions of observations taken from weather stations, ships, buoys, balloons, radiosondes, aircraft,

December 28, 2020

satellites, and other measurement platforms" [68]. It provides these estimates for the entire period over which observational records exist - from 1871 to present, interpolated over grid cells of horizontal resolution of 2° in both longitudinal and latitudinal direction. In this paper, over the area of interest 20 such points from global reanalysis domain were extracted and averaged in space, for the time period from 1871 to 2012.

3. Results

3.1. River Level Dynamics in the Vicinity of Dams

In Figure 3 we present a typical result from our DFA2 analysis of river level and flow data in the periods before damming. In all the level and flow records from hydrological stations on the four rivers that we investigated we found that DFA2 curves are approximately straight lines in log-log plots; this is in accordance with previous research. The scaling that we observed always exhibited crossover at timescales of several weeks (in the range of 15 to 40 days), with scaling exponents α_1 slightly above 1.5 for time scales below the crossover region, indicating very strong short-term autocorrelations in the small scales area, in accordance with previous studies. For this region of scales we performed a test of autocovariance difference, prescribed by [49] to assess whether values of $\alpha_1 > 1$ in this time region are due to the existence of intrinsic non-stationarities in the data that were not removed by the DFA algorithm. Our data did not show the autocovariance difference and are thus meeting this criterion. In Figure 3 we also provide DFA2 function for the series of increments $\Delta x_i = x_{i+1} - x_i$ of the original series, in the small scales region; if the original record has scaling exponent $\alpha_1 > 1$, or especially if $\alpha_1 \approx 1.5$ as in the case of our river level data, the exponent of the series of increments Δx_i should be $\alpha_\Delta = 1 - \alpha_1$ [37]. In the region of scales above the crossover all our data exhibit autocorrelated behaviour with the scaling exponents α_2 smaller than in the region below the crossover, but still in most cases with $\alpha_2 > 1$, which indicates that our records stay in nonstationary regime also in this scale range (see Figure 3). This result is somewhat in contrast with some of the observations of scaling in river flow data, including data from river Danube [37, 38], and may be manifestation of the observation that for the same river, the scaling exponent α_2 may increase down

the river, when the basin size increases [69]. In supplemental information to this paper we provide results of the surrogate data analysis for records in our dataset. We performed it to ensure that the results observed are a true characteristic of the underlying system [70]. Finally, in all the cases analyzed we found, as depicted in the inset of Figure 3, that the WTMM fractal dimension spectra $D(h)$ manifest in rather broad parabolic curves, signs of their multifractality [37, 38].

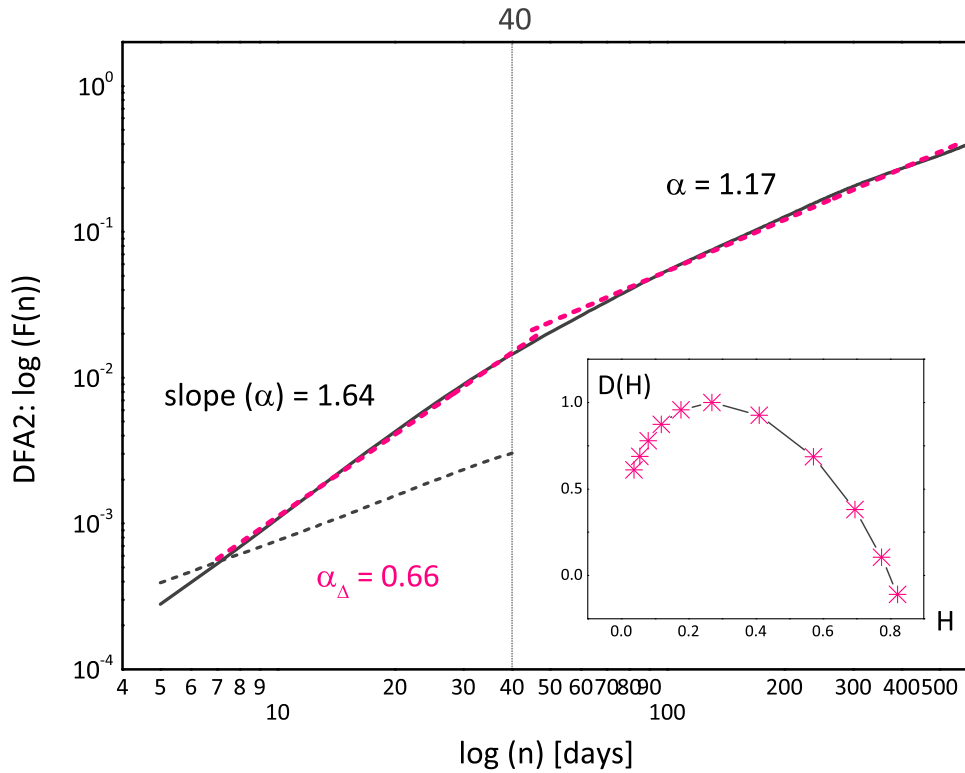


Figure 3: Typical result of the DFA2 analysis of a time series of pre-construction Danube river level from hydrological station in the vicinity of Djerdap/Iron Gates dams. DFA2 function (solid line) is given on a log-log graph, together with linear fits below and above the crossover in scaling (pink dashed lines), and the DFA2 function of the corresponding series of increments, in the small scales region (dashed line). Values of exponents α_1 and α_2 are provided; for the estimation of errors to DFA2 exponents see [71]. Inset: Singularity spectrum $D(h)$ of the WTMM method, calculated for the time series depicted in this Figure.

Our DFA2 and WTS results for the post-construction periods for hydrological stations

December 28, 2020

in the vicinity of dams show that scaling markedly depends on the position of stations in relation to dams. For the hydrological station downstream from both dams (labelled DS), we found a change of scaling dynamics in the periods after construction of dams that is evident only in the region below the crossover point. There, even if no significant change in the dynamics of the river level with the construction of dams is visible in the record (raw data, see Figure 2), the value of α_1 is significantly lowered in the period after the construction of DAM1, and this effect visibly reappears after the construction of DAM2 (see Figure 4). The WTS power spectra, depicted in Figure 4, show that these changes come about for the appearance of new cycles in the small-scales region, with amplitudes that notably decrease the scaling exponent there. In WTS these cycles appear at periods at approximately 2 days, at 3 days, at 7 days and at approximately 40 days; the 40-day cycle may be a result of prolongation of the natural 30-day river cycle [72–74] that is visible in the pre-construction period data, and it also coincides with the (new) position of the crossover in scaling. After the crossover, DFA2 functions for all three investigated time periods retain the same value of $\alpha_2 \approx 1.2$. Inspection of the local spectra of wavelet transforms (that is, the local or temporal patterns of WT coefficients) for the period 1960-1990, also presented in Figure 4, shows that the rise in values of WT coefficients of the short-term noise and the new significant cycles in WTS are apparently due to the aperiodic and probably human-related changes. This is how activities appearing in repetition on 3-40 days intervals present in DS local spectrum around the year 1965, when the damming works have started. The same pattern replicates at the end of 1970 and the beginning of 1971, when the DAM1 started operations, and in 1975, when building of DAM2 probably started. Periods of extensive reservoir and electricity production management are also visible in two additional periods - from 1979 to 1981, and from 1983 to 1986. These activities may have resulted from the rain forecasts which have been used by the operators to adjust the operation of dams, and are thus connected to the hydroclimatic phenomena, but are visibly different, more ordered and longer in duration than any of the natural events that might have triggered them.

Figure 5 presents results we obtained for the records from hydrological station upstream from both dams (denoted UP). Here the change of river level dynamics is already visible

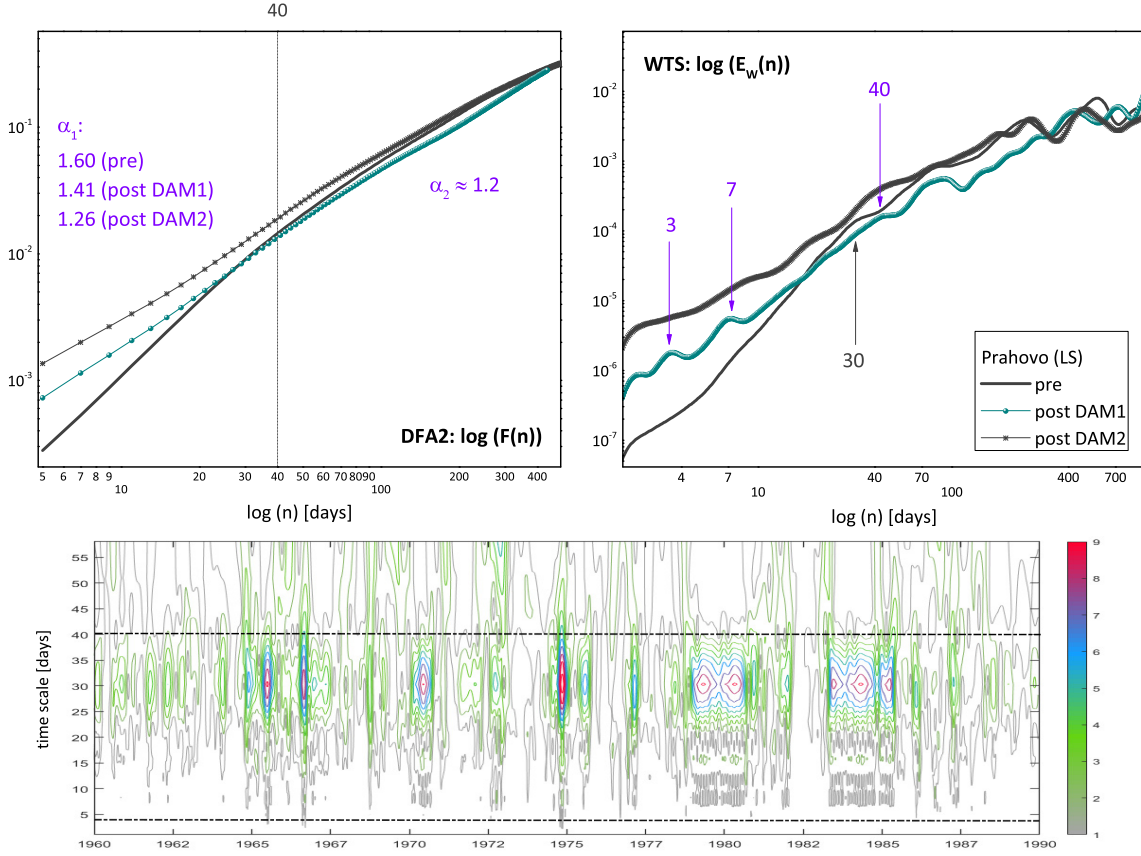


Figure 4: Results of the DFA2-WTS analysis of the time series of Danube river level records from the hydrological station Prahovo, positioned downstream from Djerdap/Iron Gates dams. (upper row, left) DFA2 functions for the period before construction of dams (gray solid lines), after the construction of DAM1 (cyan filled circles), and after the construction of DAM2 (gray asterisks), together with values of DFA2 exponents α_1 and α_2 . The approximate position of the crossover is indicated by the vertical dotted line. (upper row, right) WTS for the three construction-related time periods, with significant WTS peaks that appear in the small-scales region marked with arrows. (lower row) Local pattern of WT coefficients for the DS time series recorded in the period 1961-1990. Horizontal dotted lines at 3 days and 40 days are given as visual guides. The colorbar codes the increase of the intensity of absolute values of WT coefficients.

from the raw data (given in Figure 2). This is manifested in changes in values of α_2 , while DFA2 scaling remains unaltered in the small-scales region. The corresponding WTS functions show that, even if new cycles at approximately 2 days, at 3 days, at 7 days and at 15 days do appear in the small-scales region of WTS spectra after the construction of dams, they do not alter scaling dynamics there. The scaling after the crossover, now positioned at approximately 15 days, is altered by lowering or even loss of cyclic influence and noise at larger scales. This loss is apparent in the local WT pattern given in Figure 5, for the time period 1961-1990.

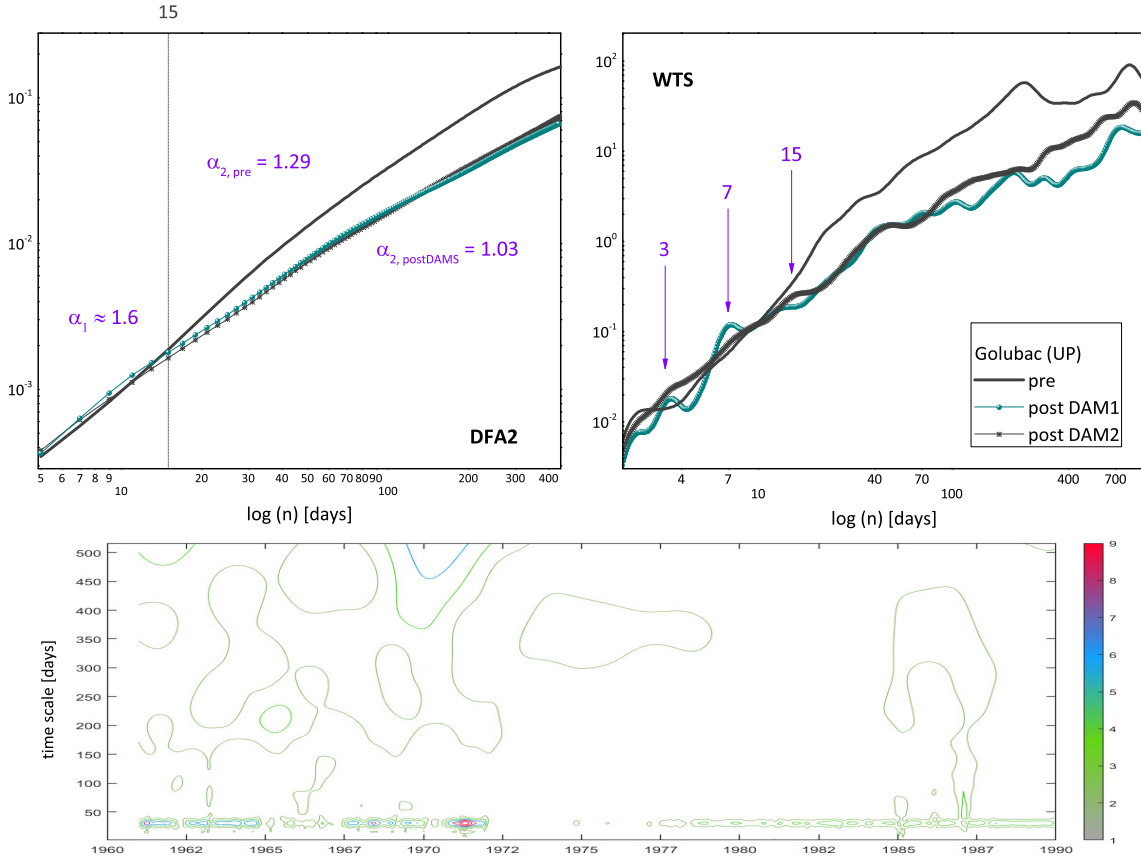


Figure 5: Results of the DFA2-WTS analysis of the time series of Danube river level records from the hydrological station Golubac, positioned upstream from Djerdap/Iron Gates dams, presented as in Figure 4.

Finally, in Figure 6 we show the extraordinary mixture of the two behavioural changes in scaling depicted above, for the records from the hydrological station Brza Palanka that

is situated between two dams. After the construction of DAM1 this station was positioned downstream from the dam and its DFA2 and WTS functions change like in the graphs presented in Figure 4: only the scaling exponent α_1 changes, decreasing in value due to the rise of amplitudes of the high frequency noise and particularly of the effects of new and/or enhanced cycles at approximately 2 days, at 3 days, at 7 days and at approximately 24 days (the last cycle also delineates the position of the crossover). After DAM2 was constructed the scaling in this station, now situated upstream from the new dam, changes in a way similar to the one depicted in Figure 5: DFA2 function has a crossover at a very small scale, after which the scaling exponent α_2 decreases significantly due to the drop in amplitude of larger-scale cycles and noise. Differently from the change in dynamics of the UP station, the reduction of the low frequency cycles and noise in MD extends only to scales up to annual after which scaling is dominated (as in the pre-development period) by the inter-annual low-frequency noise.

3.2. Changes in Natural Cycles and Influence on Multifractal Properties

To be able to study in more detail the effect of decrease of influence of large-scale natural cycles and noise in upstream water level after construction of dams, and particularly to examine modifications in the annual cycle of water level caused by damming, we calculated WTS power spectra for the original records of the three stations, as they are before deseasoning. It is important to note here that we used these calculations only to investigate behaviour of annual cycles, and not to (re)consider scaling properties. It has been shown repeatedly by other groups and by us that, when the original records are used, in the range of scales of our interest, the seasonal trend dominates DFA2 and WTS behaviour in such a profound way that the accurate estimation of scaling is impossible (see, for example, [7, 56, 75]) and thus should not be done. In Figure 7 we present results of the WTS analysis of the original (not deseasoned) data. Figure 7 clearly shows that the construction of dams is particularly connected to not just a decrease in amplitude, but even a loss of the annual cycle in the river level statistics. In order to check whether this loss is maybe prominent but in a way temporary, we did separate analysis of the data for the UP and MD stations for the period

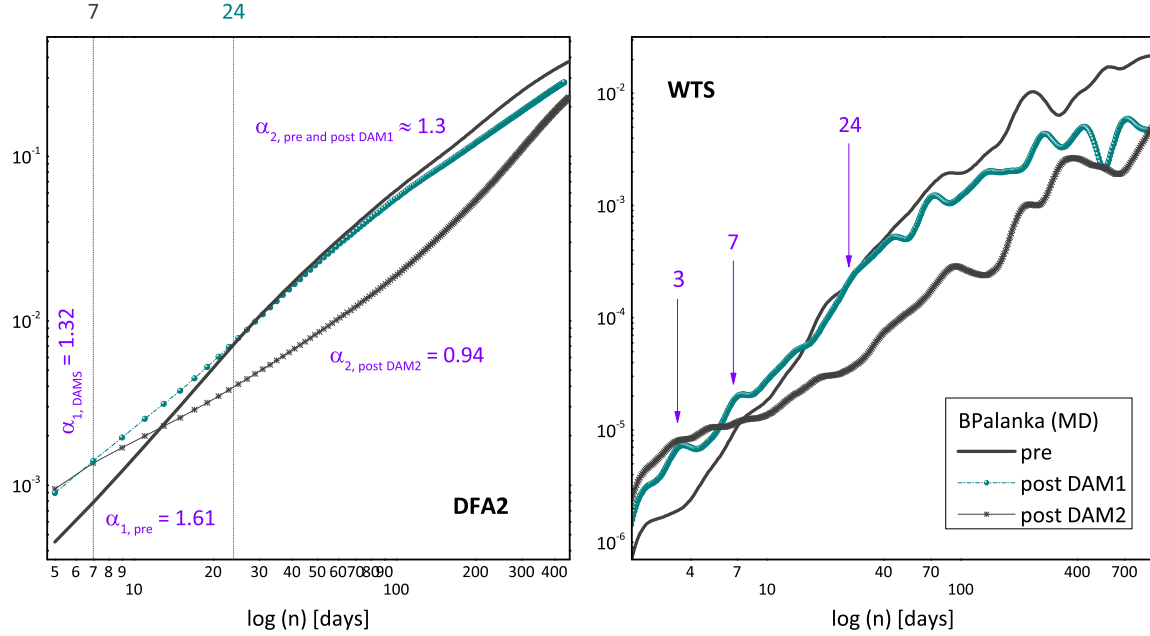


Figure 6: Results of the DFA2-WTS analysis of the time series of Danube river level records from the hydrological station Brza Palanka, positioned in between the two Djerdap/Iron Gates dams.

of 2002 to 2012 (last ten years we had in record), and we found the same WTS behaviour, that is, we found that the annual cycle is still completely (in the UP station) or partially (in the MD station) destroyed (results not shown here).

The loss of the annual cycle and partial reduction of other low frequency noises seems to additionally influence changes of multifractal character of the analyzed time series. In the pre-construction period, the WTMM analysis that we performed on all our records showed, as depicted in the inset of Figure 3, distributions of $D(h)$ as broad parabolic curves, signs of underlying multifractality and rich structure of time series [76], with slightly left-skewed shapes that speak of dominance of fractal exponents that describe the scaling of large fluctuations [76]. After damming we found that the shapes of $D(h)$ distributions changed

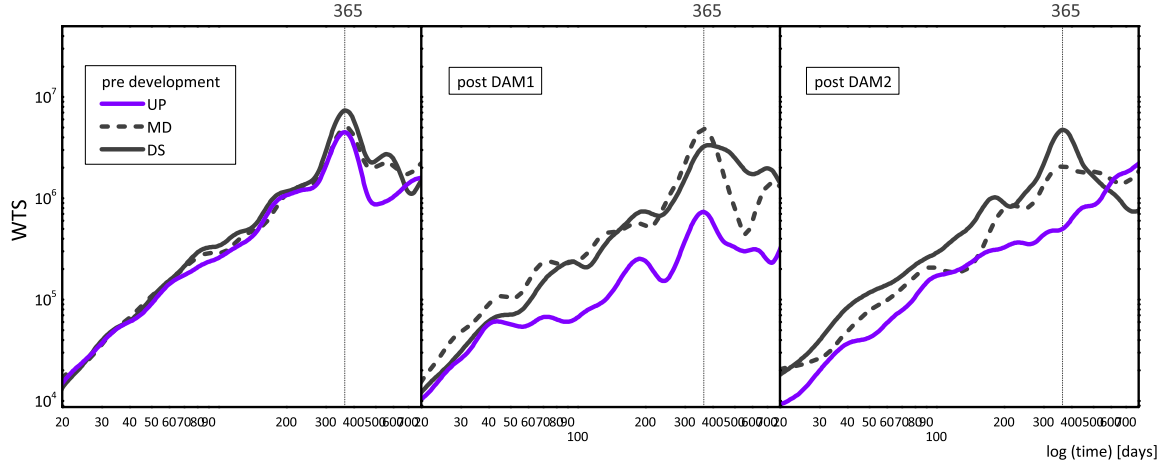


Figure 7: WTS graphs of the original (not deseasoned) records of the three hydrological stations for the three time periods related to the times of construction of Djerdap/Iron Gates dams. Dotted vertical lines at $t = 365$ days are given as visual guides. Partial destruction and the complete loss of the annual cycles are visible for stations MD (dashed line) and UP (violet line) in the time periods after the construction of dams.

for UP and MD stations, where we found visible decrease of the $D(h)$ width and change from asymmetric into a more symmetric shape, as presented in Figure 8. This would mean that the river level dynamics in the upstream stations in the vicinity of dams has lost the richness of its multifractal structure after damming, probably due to the loss of influence of some of the larger-scale phenomena. We did not find changes consistent with these in our other stations, after the damming; we did not present these WTMM results (for the stations outside of the damming area) here.

3.3. Influence of Damming on the Level and Flow Dynamics of Upstream Danube and Danube Tributaries' Stations

We analyzed data from seven hydrological stations positioned on river Danube or its three upstream tributaries. Of those the station Smederevo (D1 in our notation) is, at approximately 170 km, the closest to the dams area, while the station Bezdan (D2; 480 km away) is the most distant. For all but one of these stations we had access to the river

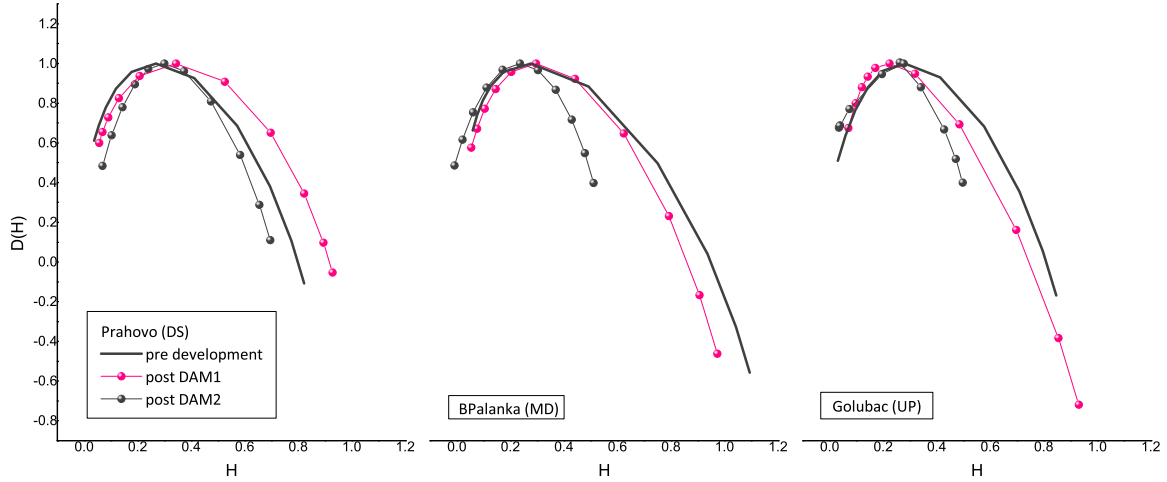


Figure 8: Distributions $D(h)$ from WTMM analysis of records from hydrological stations in the vicinity of dams, for the period before damming (solid gray line), after the construction of DAM1 (pink filled circles), and after the construction of DAM2 (grey filled circles). Shapes of $D(h)$ curves change for MD and UP stations, after the construction of dams.

flow data in addition to the river level records, which gave us the opportunity to compare dynamics of these two variables to some extent.

Of all the upstream Danube and Danube tributaries stations in our dataset, we found changes in scaling dynamics that can be connected to damming in three sets of hydrological records: in Danube upstream station Smederevo (D1), in Velika Morava tributary Ćuprija (VM1) station, and in the river Sava tributary Belgrade (S1) station. This bounds the range of effects of damming to approximately 220 km upstream from the damming area (distance of S1 from dams).

In these three stations we found visible change of behaviour in the record of river level

data, but not in the raw river flow data. In all of the three remote stations we found change in the water level accompanied with the visible decrease of level's variability, as in stations UP and MD in the vicinity of dams. In all of the three historical records - D1, VM1, and S1, we were able to only see changes induced by damming in the WTS functions of the original (before deseasoning) river level data, while the DFA2-WTS results of both the deseasoned river level and river flow data remained unaffected over time. In addition, scaling dynamics of the (deseasoned) river level and river flow records was virtually the same, within the range of error, in all of the analyzed data, with the values of scaling exponent α_2 above the crossover ranging from 0.85 to 1.1. In Figure 9 we provide graphs of the raw river level and the river flow records, together with their (before deseasoning) WTS functions, for hydrological station Smederevo (D1).

3.4. Changes in River Level Data Associated with Climate

Since the accumulated precipitation over catchment area is a major component of the hydrological cycle that determines river levels and river flows, we investigated precipitation regime over catchment area upstream from dams, trying to find similar cycles as the ones we found in post-construction river level data and thus connect those with hydroclimatic phenomena. We calculated daily accumulated precipitation, averaged over catchment area, from the 20GCR for the period 1871-2012, in order to produce historically long time series of daily precipitation that overlaps with our dataset. We calculated WTS curves and inspected the local WT patterns for deseasoned simulation series. According to results shown in Figure 10, the cycles of 15, 24 and 40 days that are present in river level data analysis can also be found in precipitation data. These cycles belong to intra-seasonal time scales and can be part of low-frequency variability modes in atmosphere. However, these cycles did not present as significant [57] in the reanalysis data, as they did in the river level records in the vicinity of dams. Diminishing significance of cycles can be a result of the process of data averaging (interpolation) within the simulation cell [75]. Local spectra of wavelet transforms of reanalysis data, given in Figure 10, show that even if cycles at 15, 24 and 40 days appear as non-periodic in 20GCR series, their appearance is, like the entire structure

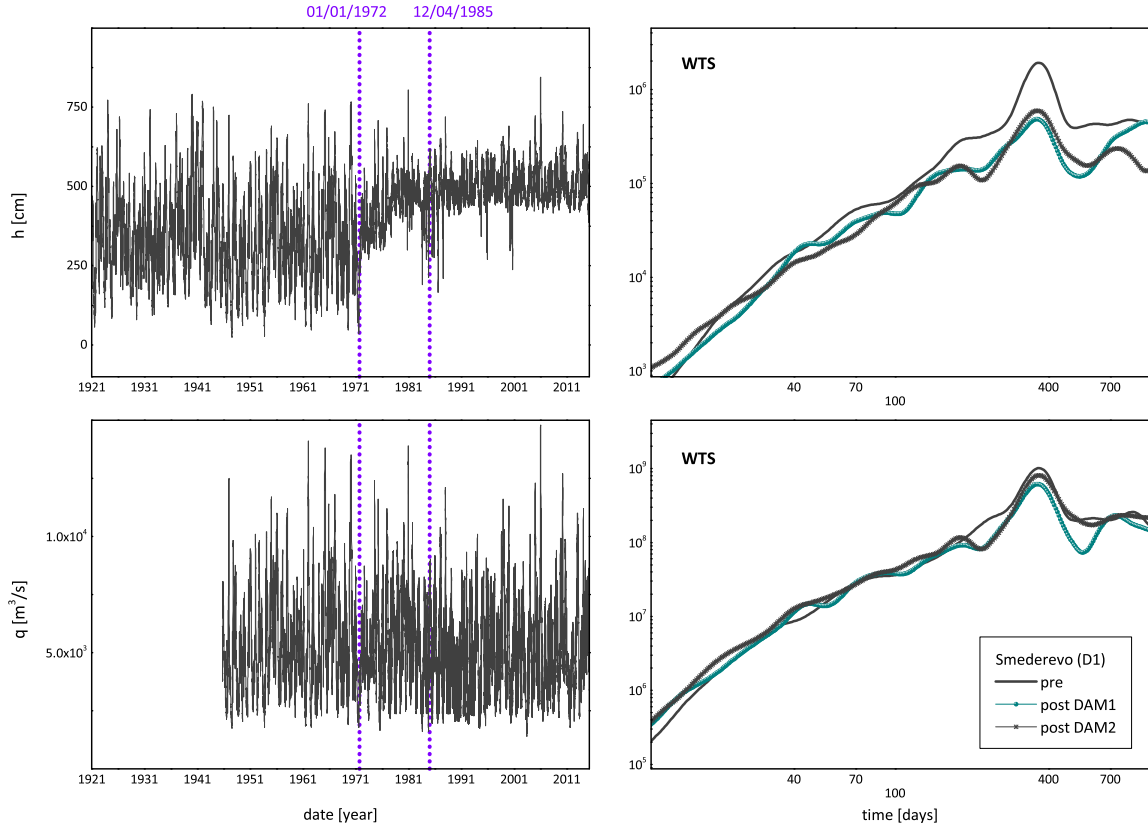


Figure 9: River level historical records (upper row, first column), starting in 1921, and their WTS functions (upper row, second column) for the three time periods, together with the river flow historical records (lower row, first column), starting in 1946, and their WTS functions (lower row, second column), for the three time periods, for the hydrological station D1 positioned on river Danube, 173 km upstream from the dams.

of precipitation local spectra, fully stochastic and very rich (in the sense that the underlying process is complex and natural). This is quite dissimilar to the local or global WT spectra presented in Figure 4, where changes in WTS behaviour stem from aperiodic but rather regular events that may be initiated by rain forecasts but are visibly different, more ordered and longer in duration than any of the natural events that might have caused them, or of the WTS presented in Figure 5, where change visibly emanates from one event, a construction of the dam. In that respect our results show that local climatic phenomena may be connected with or even may initiated changes in the dynamics or river level and flow in the vicinity of dams, but it is probably optimization of power system operation that principally determines

the character of those changes.

4. Discussion and Conclusions

In this paper we used DFA, WTS and WTMM to assess changes in long-term dynamics of Danube river level and flow associated with building of Djerdap/Iron Gates dams. We aimed at quantifying those changes to provide for characterizations that could be of use in future environmental assessments. In accordance with previous similar studies, we found scaling, or presence of long-term persistence (LTP) in all our records. We found LTP to be a sign of a high non-stationarity of our data, with scaling exponents $\alpha, \beta > 1$, and presence of crossover in scaling at scales of 7-40 days. Below the crossover, we found very strong short-term autocorrelations in all our records, with DFA2 exponent values of $1.2 \leq \alpha_1 \leq 1.65$; it was reported before that these values of α_1 indicate that the short-term (below the crossover) autocorrelations can be modelled as an ARMA processes with the characteristic autocorrelation time related to decay time of floods [38]. Above the crossover, we obtained very pronounced, in most cases non-stationary LTP, with $0.85 \leq \alpha_2 \leq 1.2$ for Danube or Danube tributaries river level. This result is somewhat different - producing larger α_2 values than reported before, from findings for Danube river flow scaling [37, 38], which may arise from the difference in the basin size [69], or may come as an effect of influence of different flood mechanisms on scaling [38]. Finally, previous researches [38] suggest that the crossover timescale found in our records is similar to the period of planetary waves, which can influence decay time of floods and thus the river level's short-term dynamics.

Our results show visible and significant impacts of development of Djerdap/Iron Gates dams on scaling of Danube river level. For time series of river level measured downstream from the damming area we found changes in scaling in the short-scales region, below the crossover. This change in short-term dynamics is brought by the general increase of amplitude of high frequency noise, and particularly by the appearance or enhancement of WTS cycles positioned at 2 days, at 3 days, at 7 days, and at 40 days. Local WT coefficients patterns configurations demonstrate that these cycles are most probably related to the timing and magnitude of the controlled release of water. The appearance of these human-made

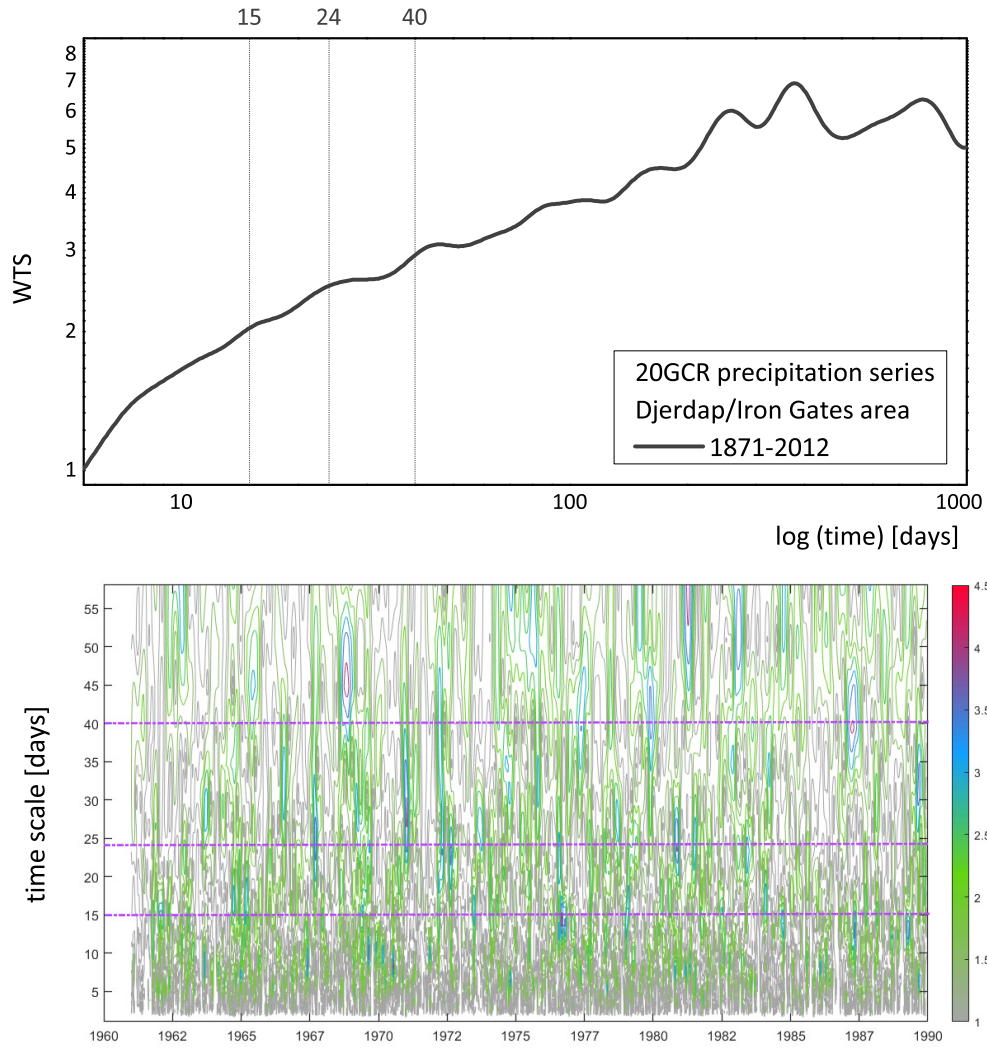


Figure 10: (upper graph) WTS of a 20GCR time series of precipitation in the period 1871-2012 in the Djerdap/Iron Gates geographical area. Vertical dotted lines at 15 days, 24 days and 40 days are given as visual guides. (lower graph) The pattern of WT coefficients for the same 20GCR time series depicted in the upper graph, for the period 1961-1990. Horizontal dotted lines at 15 days, 24 days, and 40 days are given as visual guides. Please note that the intensity of colorbar is different than in Figure 4 and Figure 5 (C).

or human-enhances cycles may reflect dams' working regime in electricity production (such as is probably the appearance of a 2-day cycle, reflecting the drop of production during weekends), or in protection of downstream area from flooding, in managing high flows at around 3-day and 7-day intervals, as well as possibly prolonging low flow durations from 30 to 40 days [72–74]. If this is the case, obtained raise in amplitude of these cycles, coupled with the loss of relative spectral contributions of other short-range noise and the decrease of values of α_1 , all confirm postulated key influence of flood mechanisms on short-term scaling of river level. This result should be further inspected for downstream hydrological stations outside of Serbia [74], due to the availability of records the geographical limit of our study, to corroborate our findings and explore spatial range of the observed effect in short-term scaling.

We furthermore found a distinct effect of damming on river level scaling upstream from Djerdap/Iron Gates dams. Even if the promotion of 2-day, 3-day, 7-day, and 15-day flow pulses regulation is visible also in the upstream WT spectra, it is the long-term scaling that is affected by damming in the upstream data, with visible decrease of values of α_2 in our DFA2 functions. Our WTS findings show that this change is mainly brought by the complete (in the vicinity of dams) or partial (further upstream) loss of the natural annual cycle, together with decrease of amplitude of other large-scales noises. This is a dramatic alteration of upstream river level dynamics. It provides information that, in addition to obvious transformation upstream of dams from a free-flowing river ecosystem to an artificial reservoir habitat [77], a major change in the river hydrodynamics also occurs as an effect of damming. Methodologically, our findings inform that seasonality is a dominant source of river level's long-term scaling, possibly coupled with influence on longer (interannual) scales that we were not able to analyse due to the finite size of our time series [75]. Practically, the observed loss of seasonality poses a substantial risk for the stability and functioning of riverine ecosystems, particularly for systems strongly adapted to seasonal and interannual flow variability, raising, among other, economic and food security concerns [78–83]. As such, this particular change should impose environmental concern or even restriction to future hydropower optimization and planning. According to our results, the alteration in

seasonality caused by damming extends beyond the reservoir, up to 220 km upstream, and affects river dynamics of Danube and of its tributaries.

Additional cycles that appeared in our WT spectra, or were enhanced by the construction of dams - the 24-day cycle in Brza Palanka (MD) station, or a 15-day and even 40-day cycles in Prahovo (DS) and Golubac (UP) stations, can not be connected to the flow regulation in a straightforward manner, and could arise as results of either pure economic, that is, human-made influence, or climatic and/or hydrodynamic events that dam construction reinforces. On the Northern hemisphere, there exist two important climatic modes of oscillation with periods near 48 and 23 days [84]. In addition, there exists a 35-40 day oscillation, characterized by blocking structure over Eurasia continent [85]. Finally, the main intra-seasonal oscillation in tropics, the Madden-Julian Oscillation (MJO), with quasi-regular period from 30 to 60 days [86] can also be linked to precipitation regimes over Europe; it has been shown that it influences the North Atlantic Oscillation (NAO) that has profound influence on European weather and climate [87]. On the other hand, regarding the (SFRY) energy planning practices and known agreements with Romania, cycles in the water levels may be expected at the intervals of 1, 7, and 365 days [34]. The longer intervals, at 15, 24, and 40 days should not be completely excluded as human-made events. They might result from rain forecasts that have been used by dam operators to adjust the operation of dams and hydro-thermal coordination, with possibility to include variable renewable energy sources. Further research in this direction may also show an intraday periodicity. Also, further studies may find changes in operation planning that occurred at the dissolving of SFRY in 1990s, and after 2000s, and/or due to wholesale electricity trade liberalization. Human-related changes described in such a way might show the path for better utilization of dams in the regional power system and at the EU wide power exchange market. Also, better utilization of dams may be obtained by including the climate change and flood control effects [88], along with ecological concerns and/or restrictions.

Finally, it remains for future studies to assess changes that we observed in multifractality of river level data, connected to the construction of dams, in a more systematic manner. Our WTMM results should particularly be considered in relation to our WTS results that

December 28, 2020

point to possible stabilization of scaling regimes in the period after the construction of the second dam. Namely, the WTS functions there do not present with appearance of new or reappearance of prominent peaks from the period after the construction of the first dam, but rather behave as WTS functions of noisy series, shifted to the new scaling regime after the construction of the first dam. This result needs to be additionally systematically studied, for similar constructions on other world rivers.

Acknowledgements

We would like to thank Davide Zanchettin and Angelo Rubino for the valuable introductory discussions on the influence of changes in river morphology to the change in river flow dynamics that lead to the formulation of this paper's research question. We are also thankful to Andreja Martinoli for an insight into the foundations of the optimal energy planning in SFRY. This work received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Grant Agreement 701785 (SB), and Serbian Ministry of Science, Education, and Technological Development grants no. 171015 (DjS and SB) and 176013 (VDj). The list of hydrological stations that are maintained by RHMZS is provided at URL <http://www.hidmet.gov.rs/eng/hidrologija/izvestajne/index.php>. Support for the Twentieth Century Reanalysis Project dataset is provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. Wavelet software was provided by C. Torrence and G. Compo, and is available at URL: <http://atoc.colorado.edu/research/wavelets/>.

References

- [1] H. E. Hurst, Long-term storage capacity of reservoirs, *Trans. Amer. Soc. Civil Eng.* 116 (1951) 770–808 (1951).
- [2] H. E. Hurst, Methods of using long-term storage in reservoirs, *ICE Proceedings* 5 (5) (1956) 519–543 (1956).

December 28, 2020

- [3] J. W. Kantelhardt, D. Rybski, S. A. Zschiegner, P. Braun, E. Koscielny-Bunde, V. Livina, S. Havlin, A. Bunde, Multifractality of River Runoff and Precipitation: Comparison of Fluctuations Analysis and Wavelet Methods, *Physica A: Statistical Mechanics and its Applications* 330 (1-2) (2003) 240–245 (2003).
- [4] A. Bunde, M. I. Bogachev, S. Lennartz, Precipitation and River Flow: Long-Term Memory and Predictability of Extreme Events, in: *Extreme Events and Natural Hazards: The Complexity Perspective*, 2013, pp. 139–152 (2013). doi:10.1029/2011GM001079.
- [5] D. Koutsoyiannis, Hydrologic Persistence and The Hurst Phenomenon, American Cancer Society, 2005, pp. 210–221 (2005). arXiv:<https://onlinelibrary.wiley.com/doi/pdf/10.1002/047147844X.sw434>, doi:10.1002/047147844X.sw434.
URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/047147844X.sw434>
- [6] B. B. Mandelbrot, J. R. Wallis, Noah, Joseph, and Operational Hydrology, *Water Resources Research* 4 (5) (1968) 909–918 (1968).
- [7] B. B. Mandelbrot, J. R. Wallis, Some long-run properties of geophysical records, *Water Resources Research* 5 (2) (1969) 321–340 (1969).
- [8] V. Livina, Y. Ashkenazy, Z. Kizner, V. Strygin, A. Bunde, S. Havlin, A stochastic model of river discharge fluctuations, in: *Physica A: Statistical Mechanics and its Applications*, Vol. 330, 2003, pp. 283–290 (2003).
- [9] M. I. Bogachev, A. Bunde, Universality in the precipitation and river runoff, *EPL* 97 (4) (2012) 48011 (2012).
- [10] A. Bunde, U. Büntgen, J. Ludescher, J. Luterbacher, H. V. Storch, Is there memory in precipitation?, *Nature Climate Change* 3 (3) (2013) 174–175 (2013).
- [11] V. Klemeš, The Hurst Phenomenon: A puzzle?, *Water Resources Research* 10 (4) (1974) 675–688 (1974).
- [12] V. Klemeš, One hundred years of applied storage reservoir theory, in: *Water Resources Management*, Vol. 1, 1987, pp. 159–175 (1987).
- [13] V. Klemeš, Water storage: Source of inspiration and desperation, in: *Reflections on Hydrology: Science and Practice*, American Geophysical Union (AGU), 2013, pp. 286–314 (2013). arXiv:<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/SP048p0286>, doi:10.1029/SP048p0286.
URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/SP048p0286>
- [14] E. Vanmarcke, *Random fields: analysis and synthesis*, MIT Press, Cambridge, MA, 1983 (1983).
- [15] O. J. Mesa, G. Poveda, The Hurst Effect: The scale of fluctuation approach, *Water Resources Research* 29 (12) (1993) 3995–4002 (1993).

- [16] E. Lundberg, K. Gardner, C. G. Druschke, B. McGreavy, S. Randall, T. Quiring, A. Fisher, F. Soluri, H. Dallas, D. Hart, Communicating about Hydropower, Dams, and Climate Change, Vol. 1, Oxford University Press, 2017 (sep 2017).
- [17] World Commission on Dams, Dams and Development: A new framework for decision-making, in: Current opinion in obstetrics {&} gynecology, Vol. 23, Earthscan Publications Ltd, London and Sterling, VA, 2000, pp. 58–63 (2000).
- [18] V. Klemeš, Geophysical Time Series and Climatic Change, Springer Netherlands, Dordrecht, 2002, pp. 109–128 (2002).
- [19] D. Koutsoyiannis, R. Ioannidis, The energetic, environmental and aesthetic superiority of large hydropower projects over other renewable energy projects, in: Proceedings of 3rd Hellenic Conference on Dams and Reservoirs, Hellenic Commission on Large Dams, Athens, 2017 (2017).
- [20] C. Teodoru, B. Wehrli, Retention of sediments and nutrients in the Iron Gate I Reservoir on the Danube River, Biogeochemistry 76 (3) (2005) 539–565 (2005).
- [21] G. Klaver, B. van Os, P. Negrel, E. Petelet-Giraud, Influence of hydropower dams on the composition of the suspended and riverbank sediments in the Danube, Environmental Pollution 148 (3) (2007) 718–728 (2007).
- [22] P. Pavlović, M. Mitrović, D. Dordević, S. Sakan, J. Slobodnik, I. Liška, B. Csanyi, S. Jarić, O. Kostić, D. Pavlović, N. Marinković, B. Tubić, M. Paunović, Assessment of the contamination of riparian soil and vegetation by trace metals - A Danube River case study, Science of the Total Environment 540 (2016) 396–409 (2016).
- [23] N. Bacalbaşa-Dobrovici, Endangered migratory sturgeons of the lower Danube River and its delta, Environmental Biology of Fishes 48 (1997) 201–207 (1997).
- [24] G. Brezeanu, O. Cioboiu, The ecological development to the Iron Gate I reservoir, in: Proceedings 36th International Conference of IAD, 2006, pp. 224–229 (2006).
- [25] V. M. Martinovic-Vitanovic, M. J. Rakovic, N. Z. Popovic, V. I. Kalafatic, Qualitative study of Mollusca communities in the Serbian Danube stretch (river km 1260-863.4), Biologia (Poland) 68 (1) (2013) 112–130 (2013).
- [26] G. Friedl, A. Wüest, Disrupting biogeochemical cycles - Consequences of damming, in: Aquatic Sciences, Vol. 64, 2002, pp. 55–65 (2002).
- [27] V. Poncos, D. Teleaga, C. Bondar, G. Oaie, A new insight on the water level dynamics of the Danube Delta using a high spatial density of SAR measurements, Journal of Hydrology 482 (2013) 79–91 (2013).
- [28] M. Mierla, G. Romanescu, I. Nichersu, I. Grigoras, Hydrological risk map for the danube delta-a case study of floods within the fluvial delta, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 8 (1) (2015) 98–104 (2015).

- [29] E. A. Levashova, V. N. Mikhailov, M. V. Mikhailova, V. N. Morozov, Natural and human-induced variations in water and sediment runoff in the Danube River mouth, *Water Resources* 31 (3) (2004) 235–246 (2004).
- [30] J. Bloesch, The ultimate need for the implementation of sturgeon protection in the Danube River Basin - a view of 2006 and call for actions with the Sturgeon Action Plan under the Bern Convention, in: *Proceedings 36th International Conference of IAD*, Vol. 132136, 2006 (2006).
- [31] J. Costlow, Y. Haila, A. Rosenholm, *Water in Social Imagination: From Technological Optimism to Contemporary Environmentalism*, Brill Rodopi, 2017 (2017).
- [32] D. Vukovic, Z. Vukovic, S. Stankovic, The impact of the Danube Iron Gate Dam on heavy metal storage and sediment flux within the reservoir, *Catena* 113 (2014) 18–23 (2014).
- [33] C. H. Lima, A. Aghakouchak, U. Lall, Classification of mechanisms, climatic context, areal scaling, and synchronization of floods: The hydroclimatology of floods in the Upper Paraná River basin, Brazil, *Earth System Dynamics* 8 (4) (2017) 1071–1091 (2017).
- [34] P. Jakovljević, *Hidroelektrane na jugoslovensko-rumunskom sektoru Dunava : Djerdap 1, Djerdap 2, Djerdap 3*, Eksport pres, Belgrade, 1979 (1979).
- [35] I. M. János, J. A. Gallas, Growth of companies and water-level fluctuations of the river Danube, *Physica A: Statistical Mechanics and its Applications* 271 (3-4) (1999) 448–457 (1999).
- [36] A. Király, I. M. János, Stochastic modeling of daily temperature fluctuations, *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* 65 (5) (2002) 051102 (2002).
- [37] E. Koscielny-Bunde, J. W. Kantelhardt, P. Braun, A. Bunde, S. Havlin, Long-term persistence and multifractality of river runoff records: Detrended fluctuation studies, *Journal of Hydrology* 322 (1-4) (2006) 120–137 (2006).
- [38] J. W. Kantelhardt, E. Koscielny-Bunde, D. Rybski, P. Braun, A. Bunde, S. Havlin, Long-term persistence and multifractality of precipitation and river runoff records, *Journal of Geophysical Research Atmospheres* 111 (1) (2006) 01106 (2006).
- [39] E. Szolgayova, J. Parajka, G. B. schl, C. Bucher, Long term variability of the Danube River flow and its relation to precipitation and air temperature, *Journal of Hydrology* 519 (PA) (2014) 871–880 (2014).
- [40] V. K. Gupta, D. R. Dawdy, Physical interpretations of regional variations in the scaling exponents of flood quantiles, *Hydrological Processes* 9 (3-4) (1995) 347–361 (1995).
- [41] RHMZS Team, *Surface Water Stations Network*.
URL {<http://www.hidmet.gov.rs/eng/hidrologija/povrsinske/index.php>}
- [42] L. A. N. Amaral, S. V. Buldyrev, S. Havlin, P. Maass, M. A. Salinger, H. E. Stanley, M. H. R. Stanley, Scaling behavior in economics: The problem of quantifying company growth, *Application of Physics in Economic Modelling* 244 (1–4) (1997) 1–24 (1997).

- [43] J. D. Fenton, R. J. Keller, The calculation of streamflow from measurements of stage, CRC for Catchment Hydrology, 2001 (2001).
- [44] R. W. Herschy, Streamflow Measurement, Third Edition, CRC Press, 2008 (2008).
- [45] K. Dahlstedt, H. J. Jensen, Fluctuation spectrum and size scaling of river flow and level, *Physica A: Statistical Mechanics and its Applications* 348 (2005) 596–610 (mar 2005).
- [46] V. Livina, Y. Ashkenazy, A. Bunde, S. Havlin, Seasonality effects on nonlinear properties of hydrometeorological records, 2011, pp. 266–284 (2011).
- [47] J. W. Kantelhardt, E. Koscielny-Bunde, H. H. Rego, S. Havlin, A. Bunde, Detecting long-range correlations with detrended fluctuation analysis, *Physica A: Statistical Mechanics and its Applications* 295 (3-4) (2001) 441–454 (2001).
- [48] C. K. Peng, S. V. Buldyrev, S. Havlin, M. Simons, H. E. Stanley, A. L. Goldberger, Mosaic organization of DNA nucleotides, *Physical Review E* 49 (2) (1994) 1685–1689 (1994).
- [49] M. Höll, H. Kantz, Y. Zhou, Detrended fluctuation analysis and the difference between external drifts and intrinsic diffusionlike nonstationarity, *Physical Review E* 94 (4) (2016) 042201 (2016).
- [50] S. Blesić, S. Milošević, D. Stratimirović, M. Ljubisavljević, Detrended fluctuation analysis of time series of a firing fusimotor neuron, *Physica A* 268 (3-4) (1999) 275–282 (1999).
- [51] S. Milošević, S. Blesić, D. Stratimirović, Beneficial randomness of signals in a neuronal circuit, in: *Physica A: Statistical Mechanics and its Applications*, Vol. 314, 2002, pp. 43–52 (2002).
- [52] C. K. Peng, S. V. Buldyrev, A. L. Goldberger, S. Havlin, M. Simons, H. E. Stanley, Finite-size effects on long-range correlations: Implications for analyzing DNA sequences, *Physical Review E* 47 (1993) 3730–3733 (1993).
- [53] M. Höll, H. Kantz, The relationship between the detrended fluctuation analysis and the autocorrelation function of a signal, *European Physical Journal B* 88 (2015) 327 (2015).
- [54] J. M. Hausdorff, C. K. Peng, Multiscaled randomness: A possible source of $1/f$ noise in biology, *Physical Review E - Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics* 54 (2) (1996) 2154–2157 (1996).
- [55] S. Mallat, W. L. Hwang, Singularity detection and processing with wavelets, *IEEE Transactions on Information Theory* 38 (2) (1992) 617–643 (1992).
- [56] K. Hu, P. C. Ivanov, Z. Chen, P. Carpena, H. E. Stanley, Effect of trends on detrended fluctuation analysis, *Physical Review E - Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics* 64 (1) (2001) 19 (2001).
- [57] D. Stratimirović, D. Sarvan, V. Miljković, S. Blesić, Analysis of cyclical behavior in time series of stock market returns, *Communications in Nonlinear Science and Numerical Simulation* 54 (2018) 21–33 (2018).

- [58] J. Morlet, G. Arens, E. Fourgeau, D. Giard, Wave propagation and sampling theory; Part II, Sampling theory and complex waves, *Geophysics* 47 (2) (1982) 222–236 (1982).
- [59] A. Grossmann, J. Morlet, Decomposition of Hardy Functions into Square Integrable Wavelets of Constant Shape, *SIAM Journal on Mathematical Analysis* 15 (4) (1984) 723–736 (1984).
- [60] M. Bračič, A. Stefanovska, Wavelet-based analysis of human blood-flow dynamics, *Bulletin of Mathematical Biology* 60 (5) (1998) 919–935 (1998).
- [61] N. M. Astaf’eva, Wavelet analysis: basic theory and some applications, *Physics-Uspekhi* 39 (11) (1996) 1085–1108 (1996).
- [62] D. Stratimirović, S. Milošević, S. Blesić, M. Ljubisavljević, Wavelet analysis of discharge dynamics of fusimotor neurons, *Physica A: Statistical Mechanics and its Applications* 291 (1-4) (2001) 13–23 (2001).
- [63] V. Perrier, T. Philipovitch, C. Basdevant, Wavelet spectra compared to Fourier spectra, *Journal of Mathematical Physics* 36 (1995) 1506 (1995).
- [64] P. Goupillaud, A. Grossmann, J. Morlet, Cycle-octave and related transforms in seismic signal analysis, *Geoexploration* 23 (1) (1984) 85–102 (1984).
- [65] C. Torrence, G. P. Compo, A Practical Guide to Wavelet Analysis, *Bulletin of the American Meteorological Society* 79 (1) (1998) 61–78 (1998).
- [66] A. Arneodo, E. Bacry, J. F. Muzy, The thermodynamics of fractals revisited with wavelets, *Physica A: Statistical Mechanics and its Applications* 213 (1-2) (1995) 232–275 (1995).
- [67] N. Scafetta, L. Griffin, B. J. West, Hölder exponent spectra for human gait, *Physica A: Statistical Mechanics and its Applications* 328 (2003) 561–583 (2003).
- [68] G. P. Compo, J. S. Whitaker, P. D. Sardeshmukh, N. Matsui, R. J. Allan, X. Yin, B. E. Gleason, R. S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R. I. Crouthamel, A. N. Grant, P. Y. Groisman, P. D. Jones, M. C. Kruk, A. C. Kruger, G. J. Marshall, M. Maugeri, H. Y. Mok, Nordli, T. F. Ross, R. M. Trigo, X. L. Wang, S. D. Woodruff, S. J. Worley, The twentieth century reanalysis project, *Quarterly Journal of the Royal Meteorological Society* 137 (654) (2011) 1–28 (2011).
arXiv:<https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.776>, doi:10.1002/qj.776.
URL <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.776>
- [69] A. Bunde, S. Lennartz, Long-term correlations in earth sciences, *Acta Geophysica* 60 (3) (2012) 562–588 (2012).
- [70] G. Lancaster, D. Iatsenko, A. Pidde, V. Ticcinelli, A. Stefanovska, Surrogate data for hypothesis testing of physical systems, *Physics Reports* 748 (2018) 1 – 60, surrogate data for hypothesis testing of physical systems (2018). doi:<https://doi.org/10.1016/j.physrep.2018.06.001>.
URL <http://www.sciencedirect.com/science/article/pii/S0370157318301340>
- [71] A. Bashan, R. Bartsch, J. W. Kantelhardt, S. Havlin, Comparison of detrending methods for fluctuation

- analysis, *Physica A: Statistical Mechanics and its Applications* 387 (21) (2008) 5080–5090 (2008).
- [72] B. D. Richter, J. V. Baumgartner, D. P. Braun, J. Powell, A spatial assessment of hydrologic alteration within a river network, *Regulated Rivers: Research & Management* 14 (2002) 329–340 (2002).
 - [73] F. J. Magilligan, K. H. Nislow, Changes in hydrologic regime by dams, *Geomorphology* 71 (2005) 61–78 (2005).
 - [74] P. Pekárová, B. Pramuk, D. Halmová, P. Miklánek, S. Prohaska, J. Pekár, Identification of long-term high-flow regime changes in selected stations along the Danube River, *Journal of Hydrology and Hydromechanics* 64 (4) (2016) 393–403 (2016).
 - [75] S. Blesić, D. Zanchettin, A. Rubino, Heterogeneity of scaling of the observed global temperature data, *Journal of Climate* 32 (2019) 349–367 (nov 2019).
 - [76] D. Stošić, D. Stošić, T. Stošić, H. E. Stanley, Multifractal analysis of managed and independent float exchange rates, *Physica A: Statistical Mechanics and its Applications* 428 (2015) 13–18 (2015).
URL [10.1016/j.physa.2015.02.055](https://doi.org/10.1016/j.physa.2015.02.055)
 - [77] International Rivers, *Environmental Impacts of Dams* (2019).
URL <https://www.internationalrivers.org/environmental-impacts-of-dams>
 - [78] J. R. Mor, A. Ruhí, E. Tornés, H. Valcárcel, I. Muñoz, S. Sabater, Dam regulation and riverine food-web structure in a Mediterranean river, *Science of the Total Environment* 625 (2018) 301–310 (2018).
 - [79] C. Yang, Y. K. Zhang, Y. Liu, X. Yang, C. Liu, Model-Based Analysis of the Effects of Dam-Induced River Water and Groundwater Interactions on Hydro-Biogeochemical Transformation of Redox Sensitive Contaminants in a Hyporheic Zone, *Water Resources Research* 54 (2018) 5973–5985 (2018).
 - [80] R. H. Guzman, A. R. Luna, C. A. B. Robles, J. T. P. Palafox, Analysis of flood pulse dynamics in the lower basin of the San Pedro River (northwestern Mexico) using remote sensing, *Latin American Journal of Aquatic Research* 44 (2016) 293–304 (2016).
 - [81] J. C. Sá-Oliveira, J. E. Hawes, V. J. Isaac-Nahum, C. A. Peres, Upstream and downstream responses of fish assemblages to an eastern Amazonian hydroelectric dam, *Freshwater Biology* 60 (2015) 2037–2050 (2015).
 - [82] R. E. Benedick, The High Dam and the Transformation of the Nile, *Middle East Journal* 33 (1979) 119–144 (1979).
 - [83] N. Nikolic, L. Kostic, M. Nikolic, To dam, or not to dam? Abolishment of further flooding impedes the natural revegetation processes after long-term fluvial deposition of copper tailings, *Land Degradation and Development* 29 (2018) 1915–1924 (2018).
 - [84] M. Ghil, K. Mo, Intraseasonal Oscillations in the Global Atmosphere. Part I: Northern Hemisphere and Tropics, *Journal of the Atmospheric Sciences* 48 (2002) 752–779 (2002).
 - [85] X. Zhang, J. Corte-Real, X. L. Wang, Low-frequency oscillations in the Northern Hemisphere, *Theo-*

- retical and Applied Climatology 57 (3) (1997) 125–133 (sep 1997).
- [86] C. Zhang, Madden-Julian Oscillation, Reviews of Geophysics 43 (2005) 2003 (2005).
- [87] C. Cassou, Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation, Nature 455 (2008) 523–527 (2008).
- [88] H. I. Eum, A. Vasan, S. P. Simonovic, Integrated Reservoir Management System for Flood Risk Assessment Under Climate Change, Water Resources Management 26 (2012) 3785–3802 (2012).